



A Reconfigurable Communications System for Small Spacecraft

Pong P. Chu
Cleveland State University, Cleveland, Ohio

Muli Kifle
Glenn Research Center, Cleveland, Ohio

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at 301-621-0134
- Telephone the NASA Access Help Desk at 301-621-0390
- Write to:
NASA Access Help Desk
NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076



A Reconfigurable Communications System for Small Spacecraft

Pong P. Chu
Cleveland State University, Cleveland, Ohio

Muli Kifle
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center

Acknowledgments

Dr. Pong P. Chu is supported by NASA/ASEE Summer 2002 Faculty Fellowship and wishes to thank the Digital Communications Technology Branch of NASA Glenn Research Center for assistance.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at <http://gltrs.grc.nasa.gov>

A Reconfigurable Communications System for Small Spacecraft

Pong P. Chu
Cleveland State University
Cleveland, Ohio 44115

Muli Kifle
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Summary

Two trends of NASA missions are the use of multiple small spacecraft and the development of an integrated space network. To achieve these goals, a robust and agile communications system is needed. Advancements in field-programmable gate array (FPGA) technology have made it possible to incorporate major communication and network functionalities in FPGA chips; thus this technology has great potential as the basis for a reconfigurable communications system. This report discusses the requirements of future space communications, reviews relevant issues, and proposes a methodology to design and construct a reconfigurable communications system for small scientific spacecraft.

Introduction

There are two important trends of NASA's future scientific missions: the use of multiple satellites and the development of an integrated space communications network. To support these trends, a new type of communications system is needed. The system has to be relatively inexpensive, flexible, robust, and able to incorporate the Open Standard Interconnection (OSI) seven-layer models (ref. 1). Field-programmable gate array (FPGA) is a technology used to construct custom digital circuits. An FPGA device consists of programmable logic cells and switching interconnects that can be reconfigured in a laboratory or in the field. Recent advancements have improved the density of the device and have made it possible to construct sophisticated systems entirely by using FPGA chips. Because of its field programmability and capacity, FPGA is a good candidate for space-based applications.

This report investigates the use of FPGA to construct a reconfigurable communications system for small space spacecraft and suggests a design methodology to achieve this goal. The next section of this report discusses future NASA communication requirements and reviews current relevant technologies. Then an overview on reconfigurable systems is provided, and the application of FPGA to a space-based communications system and its benefits are discussed. The section following reviews the platform-based design methodology and suggests the platforms needed to facilitate the design and construction of a reconfigurable communications system. The last section provides a summary.

Background

Communication Needs for Future NASA Missions

In the past, a NASA mission was normally completed by a single-spacecraft system. The spacecraft was usually large, sophisticated, and designed to satisfy the requirements of that particular mission. The onboard communications system was also customized to meet the specific need of the mission. The communications system is usually functioning as a “pipe” that transmits raw data from a satellite to a ground station or to a relay satellite as with the Tracking and Data Relay Satellite System (TDRSS) (ref. 2). The OSI model is partially incorporated in these traditional systems: even though a single-spacecraft system contains sophisticated antenna and radiofrequency (RF) circuits and utilizes complex modulation and channel coding schemes, it performs the same functionality as the physical layer of the OSI seven-layer model. As shown in figure 1, the physical layer contains multiple sublayers to perform the functions of antenna, data conversion, data formatting, and channel coding.

There is a trend in future space missions toward use of a multiple-spacecraft system—a collection of small, simple spacecraft in close coordination. Small spacecraft have the advantages of low cost, mass production, greater reliability, lower launch costs, and greater launch flexibility. Multiple-spacecraft formations have been investigated by the Air Force (refs. 3 and 4) as well as by NASA for future missions such as the Dynamic Response and Coupling Observatory (DRACO) (ref. 5) and Micro-Arcsecond X-ray Imaging Mission (MAXIM) (ref. 6). There is another trend toward developing an integrated space-based communications network. The network will facilitate the future communication needs and mirror the capability and flexibility of the terrestrial Internet (ref. 1). These trends impose new requirements on a spacecraft’s onboard communications system. First, a multiple-spacecraft system may contain up to one hundred satellites requiring close coordination for navigation, data gathering, or data processing. They essentially form an intersatellite network. Second, each spacecraft’s communications system may support the OSI upper-layer functionalities. Third, since each satellite can only accommodate a small payload, there are severe constraints on the weight and power of the communications hardware. Fourth, the multiple-spacecraft system is expected to be more flexible and able to be reconfigured to adapt to the evolving mission needs or react to new situations (ref. 7).

Review on Relevant Technology

While wireless communications and FPGA technology are active research topics, focused research on a reconfigurable communications system for space applications has just begun. However, there are several research areas that are relevant to its development. The following list summarizes their relevance to a reconfigurable communications system:

- Space-based Internet—Space-based Internet studies examine the actual network architecture and protocols, not the hardware implementations, for space applications (refs. 1 and 8).
- Wireless local area network (LAN)—Wireless LAN utilizes wireless medium, as in space communications. Its signal is relatively strong, though its distance is relatively short (up to a few hundred meters).
- Software radio—Software radio utilizes reconfigurable technology to meet different cellular communication standards (ref. 9). It is focusing on a cellular switching network rather than a general Internet application.
- Sensor network—Sensor networks use small, networked devices that collect and transmit data (refs. 10 and 11). The focus is primarily on self-reorganization, and its communications system is much more primitive than that of a spacecraft.
- Network processor—Network processors target high-speed switching and routing for terrestrial links (refs. 12 and 13). It may be overkill for the routing need of a space-based system.

- Reconfigurable computer—Reconfigurable computer studies examine the reconfigurable hardware for general applications and computation (ref. 14) but do not focus on communications systems.
- FPGA in space applications—Some researchers are interested in applying FPGA for space applications (refs. 15 and 16). However, their focus is on data processing rather than communications.

FPGA-Based Reconfigurable Communications System

Layered Model

The OSI seven-layer model divides the functions of a protocol into a series of layers. Each layer has the property that it only uses the functions of the layer below, and only exports functionality to the layer above. A system that implements protocol behaviors consisting of a series of these layers is known as a “protocol stack” or “stack.” Protocol stacks can be implemented either in hardware or software, or a mixture of both. Typically, only the lower layers are implemented in hardware, with the higher layers being implemented in software. A revised OSI layer model for a spacecraft-based communications system is shown in figure 1.

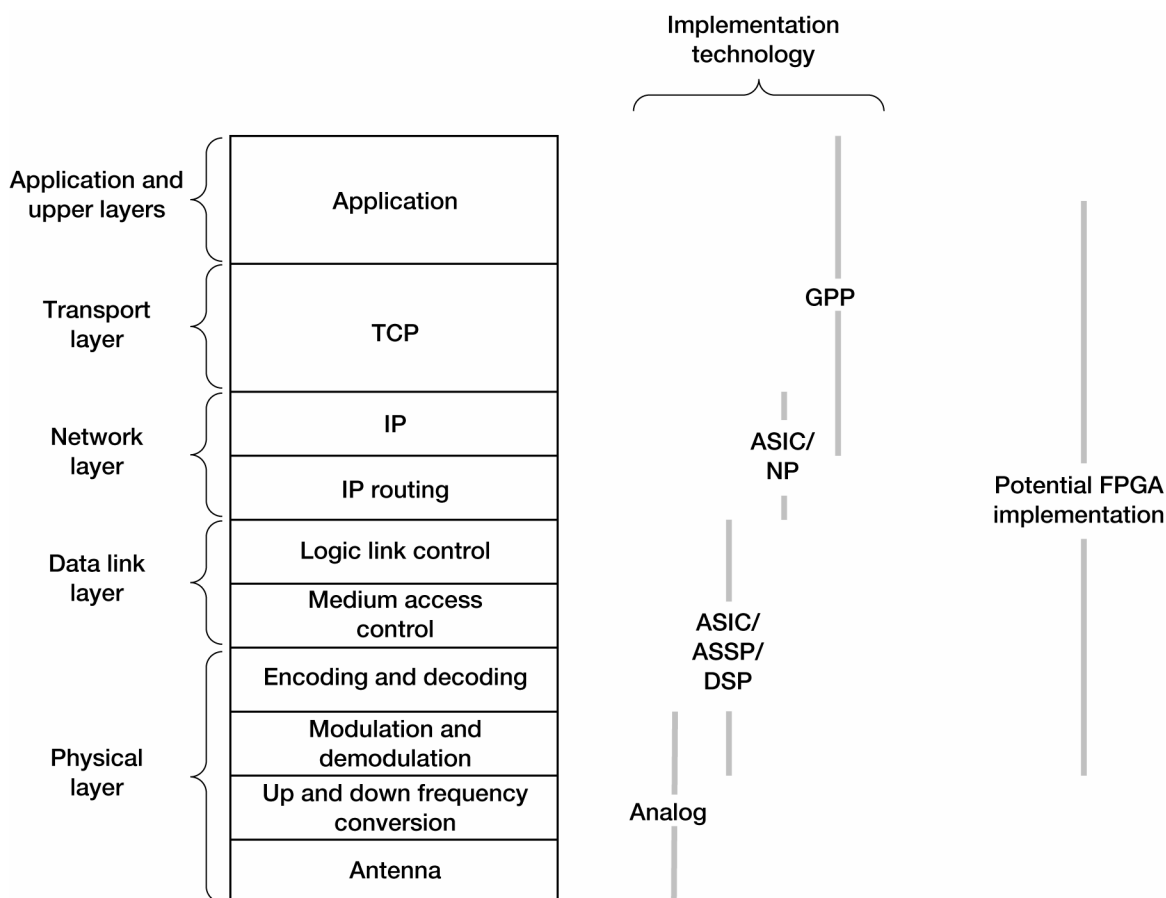


Figure 1.—Open Standard Interconnection (OSI) layer model and implementation technology. ASIC is application-specific integrated circuit; ASSP, application-specific signal processor; DSP, digital signal processor; FPGA, field-programmable gate array; GPP, general purpose processor; IP, Internet Protocol; NP, network processor; and TCP, Transmission Control Protocol.

Traditional Implementation

Because the functionalities, characteristics, and processing speeds of the OSI model layers are very different, a variety of hardware technologies is utilized to implement them. Typical implementation technologies are shown in figure 1. The physical layer is expanded to reflect the structure of a typical space-based communications system (refs. 17 and 18). The two bottom sublayers are the antenna and frequency conversion. Because of the high operating frequency, the implementation is done by analog circuitry. The next sublayer is modulation and demodulation (intermediate frequency (IF) circuit). In the past, it was also implemented by analog circuitry. As digital electronics continues to improve, it has become possible to digitize traditional analog functionalities to achieve better efficiency. This is normally done by using a high-performance digital signal processor (DSP), application-specific signal processor (ASSP), or application-specific integrated circuit (ASIC). The next sublayer is encoding and decoding. Because of the algorithm complexity and speed requirement, dedicated digital circuits are needed such as ASIC or ASSP implementations.

The data link layer, including the medium access control (MAC) sublayer, processes the data on a per-bit basis and thus still operates at a relatively high rate requiring an ASSP or ASIC chip, which is customized to a specific protocol. In the network layer, the data is processed on a per-Internet Protocol (IP)-packet basis. For a node in a LAN, it only involves the generation of an IP packet and the operation can be handled by a simple general purpose processor (GPP). On the other hand, if the node is a router, it has to do routing in real time, which involves data comparison, table looking, and buffering. This function can be performed by specialized network processors (NP) or ASIC. The Transmission Control Protocol (TCP) layer involves the establishment of the connection, generation of the TCP packet, and flow control. In a TCP packet the data is processed at a relatively low rate and can be implemented by a GPP.

Potentials of FPGA Implementation

As discussed in the previous section, several different electronic approaches are needed to construct the complete communications stack. For a regular terrestrial implementation, there are many varieties of components and technologies to choose from, and new parts are continuously being developed for new functionalities and applications. Unfortunately, most of these commercial-off-the-shelf (COTS) components cannot be used in space-based applications.

In space, high-energy particles are introduced by galactic cosmic rays and solar flares and are encountered by a spacecraft as it passes through the Earth's radiation belts. Today's sophisticated electronic devices are sensitive to these kinds of radiation and will be damaged and malfunction while exposed in this environment (refs. 19 to 21). Thus, most COTS components are unsuitable for space missions.

To overcome the radiation, special design techniques and fabrication processes have to be used. Developing a space-qualified, radiation-hardened component is very difficult. Also, because of the small number of space applications, the demand for these components is far less than for commercial components. Thus, few radiation-hardened components are developed, so there is a significant gap between space electronics and state-of-the-art technology. Ironically, while space exploration pushes the edge of science and engineering, it is limited to relatively old electronic technology. The very limited choice of modern electronic parts imposes a severe constraint on the design and implementation of a space-based communications system.

An FPGA device consists of programmable logic cells and switching interconnects that can be configured to perform a specific function. In a static random access memory (SRAM) FPGA device, the configuration information is stored in internal SRAM cells, and the device can be reconfigured by rewriting the SRAM. Radiation-hardened versions of some FPGA devices have also been developed (refs. 19, 22, and 23) and are suitable for space-based applications. In the past, programmable devices are normally used as "glue logic" for large components. However, recent advancements have improved the

density of the devices and have made it possible to construct sophisticated systems entirely using FPGA chips. Because of its field programmability, capacity, and radiation hardness, FPGA technology is a good candidate for space-based applications. It is possible to utilize FPGA technology to incorporate functions of the data link layer, network layer, transport layer, the channel encoding and decoding sublayer, and the modulation and demodulation sublayer. One or more FPGA chips will be used to replace GPP, DSP, ASSP, and ASIC components, as shown in figure 1.

The reconfigurability of FPGA technology offers a tremendous advantage for space-based applications. The major potential benefits include

- **Fabrication cost**—Unlike an ASIC that has to be fabricated in a special facility, an FPGA-based design can be constructed by configuring the SRAM in the field and involves a nonrecurring engineering (NRE) cost. This is very important for space-based applications since the demand is really small.
- **Resource sharing**—Since an FPGA chip can be configured to different functions, the hardware can be shared by different applications in a time-multiplexed fashion. For example, the same chip can be first configured for data processing and then configured as a communications system to transmit the result to a ground station. It is also possible to configure the same chip for either intranetwork communications (like LAN) or internetwork communications (between spacecraft and ground station). Since the weight and power of a small spacecraft are severely constrained, resource sharing will be extremely beneficial.
- **Adaptivity**—Since FPGA can be reconfigured in the field, the circuit can be modified to meet new missions needs or to react to unforeseen events. It can also make the communications system backward compatible (i.e., be compatible with an existing system that is still in service) or forward compatible (i.e., be compatible with future protocols).
- **Upgradeability**—Unlike ASIC or ASSP, whose functionality is fixed when fabricated, FPGA can always be upgraded in the field later when a new, more efficient algorithm or scheme is developed.
- **COTS availability**—The choices of commercial space-qualified, radiation-hardened parts are very limited. The design becomes more difficult as the number of components in a system increases. Since an FPGA chip is a generic device that can be configured for a variety of functions, only one radiation-hardened component needs to be developed. Currently, radiation-hardened FPGA parts are available from a major FPGA manufacture (refs. 22 and 23).
- **Use of latest digital technology**—Because of the requirement of radiation hardness, there is normally a 3- to 6-year gap between a state-of-the-art digital component and its space-qualified counterpart. Since an FPGA device is essentially an array of identical logic cells, developing a radiation-hardened version is relatively simple, and its capability is closer to state-of-the-art technology.

Design Approach

Platform-Based Design Methodology

A reconfigurable communications system is a very complex implementation. First, protocols have to be implemented in upper OSI layers as well as coding and modulation schemes implemented in the physical layer. Second, these protocols and schemes are not fixed, and a protocol and scheme can be replaced if needed. The ability to manage complexity is a key factor for a successful construction. This project will use a methodology known as “platform-based design” (refs. 24 and 25), which divides the system into manageable levels and facilitates architecture flexibility and design reuse.

A platform can be thought of as a set of common core functions that are needed by an application domain. A diagram illustrating the relationship between application domains, platforms, and implementation is shown in figure 2. A platform is essentially an abstraction that shields unnecessary implementation details from the lower level. For a complex system, this abstraction has to be done in several levels, and a sequence of platforms is needed. The implementation of a higher level platform

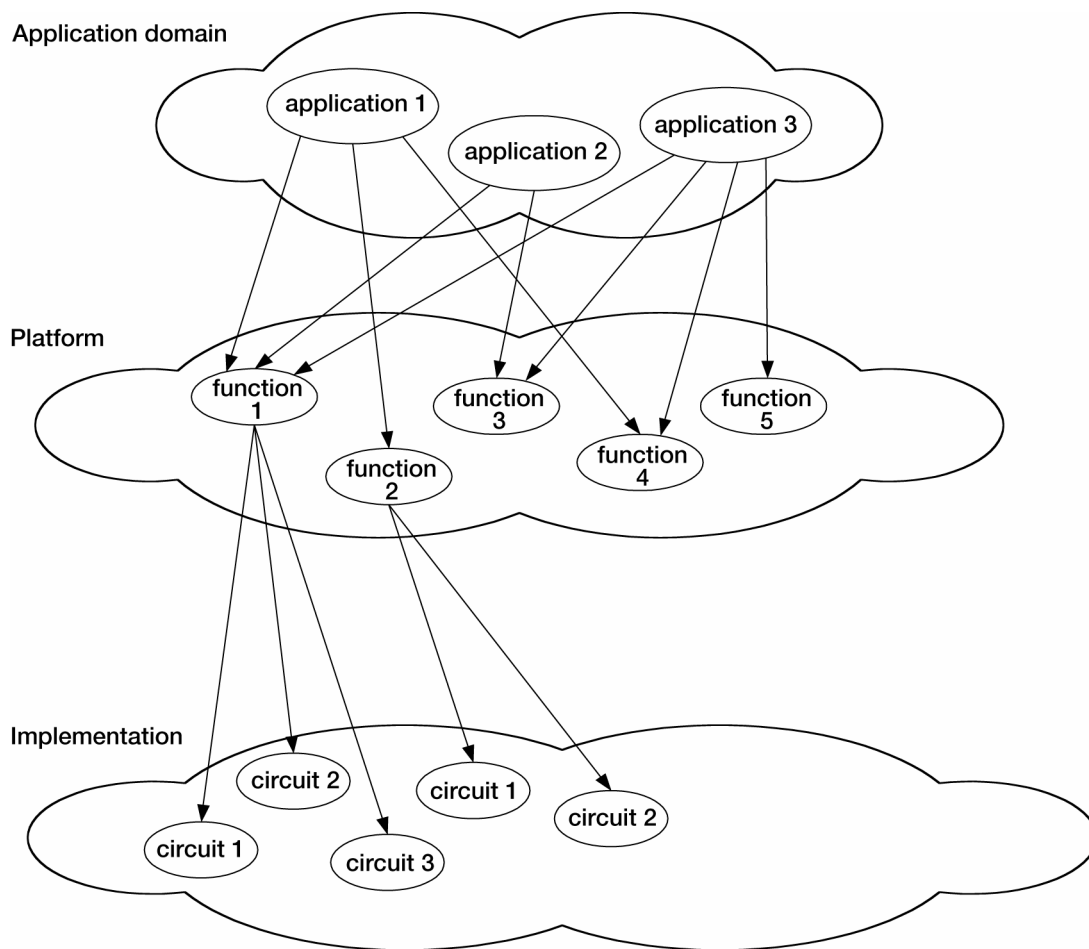


Figure 2.—Platform concept for spacecraft reconfigurable communications system.

becomes the application domain of a lower level platform. For example, digital modulation can be considered as an application domain that includes various modulation schemes. Implementations of these modulation schemes are different but may use some common functions, such as integer multiplication, discrete Fourier transformation, and accumulation. These core functions constitute the platform for digital modulation schemes. The platform only specifies what the functions are, not how they are implemented. The functions may be implemented in programmable logic cells or circuits.

In addition to the complex management, the platform-based design has two other major benefits. First, this methodology encourages design reuse. Instead of designing a circuit for every new application, this approach identifies the core building blocks for a set of similar applications and lets different applications use the same building blocks. When a new application needs a nonexistent block, the block has to be designed from scratch. However, once the block is completed, it can be put into the platform and becomes part of the inventory that can be used in future applications. Second, this methodology facilitates the reconfiguring process. The platform-based design establishes a collection of components at each level. Reconfiguration can be accomplished by selecting the proper components and “plugging” them into the system.

Identification of Platforms

The platforms for spacecrafts' communications systems should follow the expanded OSI layer model in figure 1. The primitive investigation has identified five application layers: TCP/IP, network routing, data link, channel encoding and decoding, and modulation and demodulation. For each platform, functionality, operation speed, and implementation complexity must be considered. Operation speed frequently is a major criterion in a communications system. While the same amount of information is passed through communication layers, the required operation speed is different for each platform. For example, in a TCP/IP platform, information is processed on a per-packet basis. Since a packet contains at least several hundred bits (for example, there are 24 bytes in a TCP packet header), the processing rate is only about one-thousandth of the bit rate. On the other hand, in a modulation/demodulation platform, the analog signal has to be oversampled and digitized, and the processing rate can be much higher than the bit rate.

The following sections give a general overview on the functionality and processing speed of each platform and provide an initial assessment on the complexity of FPGA implementation. The implementation of all modules will be done using very high speed integrated circuit hardware description language (VHDL) and will then be synthesized to the chosen FPGA device.

TCP/IP.—This platform implements the TCP and nonrouting part of the IP. Its functions include the establishment and termination of a connection, flow control, fragmentation and reassembly, and address resolution. The data in this level is processed on a per-packet basis. Because this processing rate is much slower than bit rate, the processing can be handled by GPP, and the functions are normally implemented using software routines, frequently known as I/O drivers. Since the goal is to implement the entire communications system in a single FPGA chip, no external processor will be used. There are two possible ways to implement the functions: One is to construct a small embedded GPP and develop the driver code accordingly. The alternative is to derive an extended finite-state machine to follow the transactions defined in the protocol and then to develop the hardware.

Network routing.—This platform implements the routing part of the IP. Its functions include address filtering, table searching, buffering, etc. The data is processed in this level on a per-packet basis. However, instead of processing one packet at a time, the router has to handle multiple incoming links and outgoing links concurrently and thus demands more computation power. In terrestrial network, high-speed routing is normally done by an NP or ASSP. Since a multiple-spacecraft system is a small, self-contained network, it should not have a large number of incoming and outgoing links. The routing table and necessary functions can be implemented in an FPGA.

Data link and MAC.—This platform implements the functions of the data link layer protocol. While most functions, such as flow control, are processed on a per-packet basis, the others, such as the generation and checking of the error control code, are processed on a per-bit basis. To handle the bit stream, the processing rate has to be increased significantly. However, since most functions in this platform are fairly simple, they can be implemented in an FPGA.

Channel encoding and decoding.—This platform implements the functions for channel encoding and decoding for communication channels (refs. 18 and 26). Because of the weak signal power and high noise level, powerful channel encoding and decoding schemes have to be used. The channel codes must be powerful enough for the low-signal-to-noise-ratio environment, yet relatively simple for implementation in an FPGA. Traditional codes for satellite communications like convolutional codes, BCH (Bose, Chaudhuri, and Hocquenghem) codes, and RS (Reed-Solomon) codes can be considered. Recently developed turbocodes are powerful, but require a sophisticated decoder. New types of codes called concatenated tree (CT) codes have near-optimal performance and are very easy to decode.

Modulation and demodulation.—This platform implements functions for digital modulation and demodulation schemes, which utilize digital electronics for IF circuitry (refs. 26 and 27). There are two possible approaches: One is to “digitize” traditional schemes, such as binary phase-shift keying (BPSK) or quadrature phase-shift keying (QPSK). The other is to use orthogonal frequency division multiplexing (OFDM), in which modulation and digitization are naturally combined in one step using digital signal

processing. The functions necessary to implement these schemes include multiplication, DFT and inverse DFT, digital filtering, etc. Digital demodulation has to sample the analog waveform and convert it via an analog-to-digital (A/D) converter. The sampling and A/D conversion significantly increase the data rate, which can be much higher than the bit rate. While today's FPGA devices should be able to implement the required functions, it is unclear whether they can provide enough computation power to meet the stringent processing requirements. In light of this, OFDM has an advantage in that the sampling rate is significantly lowered by dividing the data stream into multiple data streams of lower rates.

Conclusions

A networked and reconfigurable communications system is needed for NASA's future small spacecraft. Because of its field programmability, capacity, and radiation hardness, field-programmable gate array (FPGA) technology can be used to construct these systems. FPGA chips can be designed to incorporate communication and network functionalities and thus replace all individual application-specific signal processor (ASSP), digital signal processor (DSP), and general purpose processor (GPP) components. A platform-based design methodology that facilitates architecture flexibility and design reuse will be used to divide the system into manageable levels. The recommended platforms are Transmission Control Protocol/Internet Protocol (TCP/IP), network routing, data link, channel encoding and decoding, and modulation and demodulation.

References

1. Bhasin, K.; and Hayden, J.L.: Space Internet Architectures and Technologies for NASA Enterprises. 2001 IEEE Aerospace Conference Proceedings, vols. 1–7, 2001, pp. 931–941.
2. Brandel, Daniel L.; Watson, William A.; and Weinberg, Aaron: NASA's Advanced Tracking and Data Relay Satellite System for the Years 2000 and Beyond. IEEE Proc., vol. 78, 1990, pp. 1141–1151.
3. Das, Alok; and Cobb, Richard: TechSat 21—Space Missions Using Collaborating Constellations of Satellites. Proceedings of the 12th AIAA/USU Conference on Small Satellites, Logan, UT, 1998.
4. Martin, M.; and Kilberg, S.: TechSat 21 and Revolutionizing Space Missions Using Microsatellites. Proceedings of the 15th AIAA/USU Conference on Small Satellites, Logan, UT, 2001.
5. Magnetospheric Constellation (MC). <http://stp.gsfc.nasa.gov/missions/mc/mc.htm> Accessed Mar. 29, 2004.
6. Micro-Arcsecond X-ray Imaging Mission—MAXIM. <http://maxim.gsfc.nasa.gov/> Accessed Mar. 4, 2003.
7. Prescott, G.E.; Smith, S.A.; and Moe, K.L.: Information System Technology Challenges for NASA's Earth Science Enterprise. Proceedings of the Geoscience and Remote Sensing Symposium, vol. 1, IEEE, Piscataway, NJ, 2001, pp. 436–438.
8. Cutler, J.W.; Fox, A.; and Bhasin, K.: Applying the Lessons of Internet Services to Space Systems. Proceedings of the IEEE Aerospace Conference, vol. 7, IEEE, Piscataway, NJ, 2002, pp. 7–3287–7–3295.
9. Srikanteswara, S., et al.: A Soft Radio Architecture for Reconfigurable Platform. IEEE Commun. Mag., vol. 38, issue 2, 2000, pp. 140–147.
10. Lim, A.: Distributed Services for Information Dissemination in Self-Organizing Sensor Networks. J. Franklin Inst., vol. 338, no. 6, 2001, pp. 707–727.
11. Sohrabi, K., et al.: Protocols for Self-Organization of a Wireless Sensor Network. IEEE Personal Communications, vol. 7, no. 5, 2000, pp. 16–27.

12. Braun, F.; Lockwood, J.; and Waldvogel, M.: Protocol Wrappers for Layered Network Packet Processing in Reconfigurable Hardware. *IEEE Micro*, vol. 22, no. 1, 2002, pp. 66–74.
13. Lockwood, J.W., et al.: Reprogrammable Network Packet Processing on the Field Programmable Port Extender (FPX). *Proceedings of the ACM/SIGDA International Symposium on Field Programmable Gate Arrays*, 2001, pp. 87–93.
14. Hauck, S.: The Roles of FPGA's in Reprogrammable Systems. *Proceedings of the IEEE*, vol. 86, no. 4, 1998, pp. 615–638.
15. Conde, Richard F., et al.: Adaptive Instrument Module—A Reconfigurable Processor for Spacecraft Applications. *Proceedings of the Second MAPLD 1999—Annual Military and Aerospace Applications of Programmable Devices and Technologies Conference*, Laurel, MD, 1999.
16. Figueiredo, M.A., et al.: Extending NASA's Data Processing to Spacecraft. *Comput.*, vol. 32, no. 6, 1999, pp. 115–118.
17. Richharia, M.: *Satellite Communication Systems: Design Principles*. McGraw-Hill, New York, NY, 1999.
18. Roddy, Dennis: *Satellite Communications*. Third ed., McGraw-Hill, New York, NY, 2001.
19. Katz, R., et al.: Radiation Effects on Current Field Programmable Technologies. *IEEE Trans. Nucl. Sci.*, vol. 44, no. 6, part 1, 1997, pp. 1945–1956.
20. Sexton, F.W., et al.: Qualifying Commercial ICS for Space Total-Dose Environments. *IEEE Trans. Nucl. Sci.*, vol. 39, no. 6, part 1, 1992, pp. 1869–1875.
21. Stassinopoulos, E.G.; and Raymond, J.P.: The Space Radiation Environment for Electronics. *Proceedings of the IEEE*, vol. 76, no. 11, 1988, pp. 1423–1442.
22. Carmichael, Carl; Fuller, Earl; and Caffrey, Michael: SEU Mitigation Techniques for Virtex FPGAs in Space Applications. *Proceedings of the Second MAPLD 1999—Annual Military and Aerospace Applications of Programmable Devices and Technologies Conference*, Laurel, MD, 1999.
23. Fabula, Joe; and Bogrow, Howard: Total Ionizing Dose Performance of SRAM-Based FPGAs and Supporting PROMs. Paper presented at the 2000 MAPLD International Conference, Laurel, MD, 2000.
24. Ferrari, A.; and Sangiovanni-Vincentelli, A.: System Design: Transitional Concepts and New Paradigms. *Proceedings of the International Conference on Computer Design*. Austin, TX, 1999.
25. Sgroi, M., et al.: Formal Models for Embedded System Design. *IEEE Design Test Comp.*, vol. 17, no. 2, 2000, pp. 14–27.
26. Proakis, John G.: *Digital Communications*. Third ed., McGraw-Hill, New York, NY, 1995.
27. Xiong, Fuqin: *Digital Modulation Techniques*. Artech House, Boston, MA, 2000.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE May 2004		3. REPORT TYPE AND DATES COVERED Technical Memorandum
4. TITLE AND SUBTITLE A Reconfigurable Communications System for Small Spacecraft			5. FUNDING NUMBERS WBS-22-704-60-14	
6. AUTHOR(S) Pong P. Chu and Muli Kifle				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-14098	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-2004-212534	
11. SUPPLEMENTARY NOTES Pong P. Chu, Cleveland State University, Cleveland, Ohio and NASA Summer Faculty Fellowship at Glenn Research Center; and Muli Kifle, NASA Glenn Research Center. Responsible person, Muli Kifle, organization code 5650, 216-433-6521.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category: 17 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Two trends of NASA missions are the use of multiple small spacecraft and the development of an integrated space network. To achieve these goals, a robust and agile communications system is needed. Advancements in field programmable gate array (FPGA) technology have made it possible to incorporate major communication and network functionalities in FPGA chips; thus this technology has great potential as the basis for a reconfigurable communications system. This report discusses the requirements of future space communications, reviews relevant issues, and proposes a methodology to design and construct a reconfigurable communications system for small scientific spacecraft.				
14. SUBJECT TERMS Space communication; Field-programmable gate arrays; Reconfigurable hardware			15. NUMBER OF PAGES 15	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	

